Detection of a CMB decrement towards the $z = 3.8$ quasar pair PC1643+4631 A & B

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ABSTRACT

In a 15-GHz Ryle-Telescope observation of PC1643+4631 A & B, a pair of quasars at redshifts $z = 3.79$ and 3.83 separated by 198″ on the sky, we find a decrement in the cosmic microwave background (CMB) of -380 ± 64 μJy in a $110'' \times 175''$ beam. Assuming this to be a Sunyaev-Zel'dovich effect due to an intervening cluster, the minimum magnitude of the central temperature decrement is 560 μK. A serendipitous ROSAT observation shows that there is no X-ray-luminous cluster in the direction of the decrement at $z < 1$. The implied gas mass is $\gtrsim 2 \times 10^{14}$ $M_\odot$ (assuming a temperature of ~ 5 keV), indicating a total mass of $> 10^{15}$ $M_\odot$. This result demonstrates the existence of a massive system too distant to be detected by its emission, but which can be found via its imprint on the CMB.

Subject headings:

Cosmic microwave background—quasars:individual:PC1643+4631 A & B—galaxies:clusters

1. Introduction

Clusters of galaxies are difficult to identify optically at high redshift because of the rapid decrease of surface brightness with redshift and because of confusion with the foreground field. X-ray surveys have successfully detected clusters out to redshifts z of 0.5–1 (e.g. Gioia et al. 1990), but are biassed towards finding only the very richest clusters due to the strong dependence of X-ray luminosity on gas density. The Sunyaev-Zel'dovich (S-Z) effect (Sunyaev & Zel'dovich 1972) is a potentially very useful tool for finding and studying high-redshift clusters because its magnitude is independent of redshift, with only the angular size of the effect changing with z. Observing techniques have advanced sufficiently that there have now been detections of the S-Z effect in several clusters (e.g. Birkinshaw et al. 1984; Jones et al. 1993; Wilbanks et al. 1994;

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Herbig et al. 1995). Our own S-Z programme with the Ryle Telescope (RT; Jones 1991) operating at 15 GHz has produced S-Z images of several moderately distant ($0.15 < z < 0.55$) clusters (e.g. Grainge et al. 1993; Saunders 1995; Grainge et al. 1996). We report here the results of our initial programme to obtain S-Z detections of more-distant systems.

2. Observing Strategy

We chose to observe the fields of radio-quiet quasars, for two reasons. First, quasars have long been expected to exist in high density regions and observations of quasar companions support this (e.g. Hu, McMahon & Egami 1996). Second, high-redshift quasars may serve as markers for intervening gravitational lenses which magnify them. We drew up a list of northern quasars at $z > 1$ with a 5-GHz flux density of < 1 mJy (in order to minimize the contamination of any S-Z signal by radio emission from the quasar itself) and checked that the chosen fields did not contain any known foreground clusters. These criteria produced a list of about thirty candidate quasars, of which three were chosen for initial observation on the basis of how well their positions would fit in with the rest of the RT observing programme. The targets were PG0117+213, MS00365 and PC1643+4631A & B; the radio observations are now described.

3. Radio observations

The RT is an nearly east-west, aperture-synthesis telescope operating at 15 GHz, with eight 13-m-diameter antennas. For this experiment only five antennas were used, in an array giving projected baselines from 13 to 108 m (0.65–5.4 kλ) (Grainge et al. 1996). In this configuration the system temperature of 75 K and bandwidth of 350 MHz give a sensitivity of 200 μJy in 12 h in a synthesised beam of FWHM $30'' \times 30''\mathrm{cosec}\delta$, with an envelope beam of $6'$ FWHM. For each field, observations of a phase calibrator are interleaved with the main observation at intervals of about 20 min, and a primary flux calibrator (either 3C286 or 3C48) observed before or after the run. Visibilities taken when the telescope was driving between source and calibrator are flagged out, as are those in which one antenna is shadowed by another, or in which the real or imaginary part is greater than 3.5 times the rms for that run. (Only a very small fraction of the data is lost by this amplitude cut, which is done to remove rare interference spikes.) A map is made of each observation as a check for problems, and the files are then concatenated. The S-Z signal from a cluster falls very rapidly with increasing baseline, whereas most radiosources are unresolved on all our baselines. We therefore use the 1.25–5.4 kλ data to estimate the source flux densities and positions and subtract them from the 0.65–1.25 kλ data.

This procedure has been used successfully to map the S-Z effect in more than 10 X-ray-selected clusters (e.g. Saunders 1995); in each case the S-Z image has been consistent with the X-ray data. Very long integrations with the RT have shown no evidence for any artefacts, and we are confident

that this observing process is robust.

3.1. MS00365 and PG0117+213

MS00365 is an X-ray-selected quasar at $z = 1.25$ (Stocke et al. 1991). It was observed with the RT on 14 occasions in 1995 June and July, using 0007+171 as a phase calibrator. The map of all the data had a noise level of 70 μJy beam^{-1}, and no features brighter than 240 μJy beam^{-1} (3.4 σ). No sources were subtracted. The map of baselines shorter than 1.25 kλ had a noise level of 178 μJy beam^{-1}, and no features brighter than 520 μJy beam^{-1} (2.9 σ).

PG0117+213 is a quasar at $z = 1.49$ with several Ly-α absorption systems (Lanzetta et al. 1995). We observed it with the RT on 8 occasions in 1994 April and May, with 0149+218 as phase calibrator. No significant features were apparent on either the 1.25–5.4 kλ or 0.65-1.25 kλ maps, which had noise levels of 80 and 180 μJy beam^{-1} respectively.

3.2. PC1643+4631

The quasar pair PC 1643+4631 A & B was discovered on the basis of strong emission lines in the Palomar Transit Grism Survey (see Schneider, Schmidt & Gunn 1994). Optical spectra, giving redshifts of $z = 3.79$ and $z = 3.83$ respectively, have been published by Schneider, Schmidt & Gunn (1991). Schneider et al. 1991 give r_4 magnitudes of 20.3, 20.6 for A, B respectively; both are radio quiet. The quasars lie 198$''$ apart on the sky, corresponding to a projected distance of 1.3 Mpc (we take $H_0 = 50$ km s^{-1}Mpc^{-1}, $\Omega = 1$ and $\Lambda = 0$). There is a damped Ly-α absorption system at $z = 3.14$ in the spectrum of quasar A, making it the subject of many recent observational programmes (e.g. Hu & Ridgway 1994).

We observed PC1643+461 on 44 occasions between 1994 March and 1995 June, pointing the telescope mid-way between the two quasars (at $16^{\rm h}43^{\rm m}43^{\rm s} + 46°31'20''$; all positions are B1950.0). The phase calibrator was 1624+416, which has a 15-GHz flux density of 1.1 Jy. Fig. 1 shows the CLEANed map of the 1.25–5.4 kλ data. The noise level is 33 μJy beam^{-1}. Two point sources are evident: 550 μJy at $16^h43^m53^s.9 + 46°31'10''$, and 200 μJy at $16^h43^m44^s.9 + 46°29'32''$. These were subtracted from the visibilities and another 1.25–5.4 kλ map made. A third source was found of 150 μJy at $16^h43^m55^s.4 + 46°29'40''$; it also was subtracted.

We then made a map of the baselines shorter than 1.25 kλ. This showed a negative source of -387 ± 75 μJy, centred at $16^{\rm h}43^{\rm m}44^{\rm s}.0 + 46°30'20''$, some 60$''$ south of the pointing position. Although this is close to the position of the 200-μJy source we subtracted, the magnitude of the negative source is > 10 times the uncertainty in the subtracted flux, and if the subtracted source were resolved on the short baselines we would expect to see excess positive, not negative, flux. To check for possible systematic effects we divided the data into two independent sets, first

by frequency channel and then by time, and re-made the maps; in each case the divided maps were consistent with the summed map. We re-observed the field for a further 10 days with the pointing centre shifted $40''$ south; after subtracting sources using the same technique as before, the 0.65–1.25 kλ map was consistent with the previous result, showing a decrement of -460 ± 150 μJy at the same position. We then made a combined map using the data from both pointings, taking into account the differing envelope beam attenuations. This map is shown in Fig. 2, which has been CLEANed with a restoring beam of $110'' \times 175''$. The peak flux density is -380 ± 64 μJy beam^{-1} and the integrated flux is -410 μJy, i.e. the source is not significantly extended on this map. The positional accuracy of the centre of the decrement is roughly the beamsize divided by the signal-to-noise ratio, i.e. about $20'' \times 30''$.

4. X-ray observations of PC1643+4631

The field of PC1643+4631 was serendipitously observed in a ROSAT PSPC observation of the cluster A2219. The quasar pair is $52'$ from the centre of the PSPC observation, so the effects of vignetting and degraded point-spread function are severe, but nevertheless this observation provides a limit to the X-ray flux from the region. In the total exposure of 11.2 ks, 812 counts were detected within a radius of $5'$ of the decrement (roughly equal to the size of the local point-spread function). The backgrounds measured in similar regions of the detector predict a total of 863 ± 30 counts from this region, giving a 3-σ upper limit of 90 counts above the background. This corresponds to an unabsorbed flux of 1.7×10^{-16} W m^{-2} in the energy range 0.1–2.4 keV (observed). Assuming a temperature of 5 keV and a redshift of $z = 1$, this corresponds to an X-ray luminosity of $< 7 \times 10^{37}$ W.

5. Discussion

The most conservative assumption is that we have detected an S-Z effect due to a previously unknown cluster. Primordial CMB anisotropies are expected to have much smaller amplitudes on arcminute scales. We have investigated (Lasenby et al. in preparation) the possibility that the decrement is due to the Rees-Sciama effect (the change in CMB photon energy on passing through the gravitational potential of a collapsing object) and it seems very difficult to produce a significant signal even in extreme cases.

Since the redshift of the cluster is not known and the S-Z decrement is only detected on a very restricted range of baselines, we have little information on the angular extent of the decrement. However, the *minimum* magnitude of central decrement is obtained when the cluster just fills the synthesised beam: if the cluster is smaller than the beam then there is beam dilution and the observed signal falls; if the cluster is larger than the beam then the signal is resolved and again falls. Modelling the cluster as a spherical King model with an angular dependence of

$\Delta T = \Delta T_0(1+\theta^2/\theta_c^2)^{\frac{1}{2}-\frac{3}{2}\beta}$ with $\beta = 2/3$, the minimum magnitude of ΔT_0 consistent with our data is 560 μK; the corresponding value of θ_c is about $60''$.

We can put a constraint on the minimum redshift of the hot gas from the lack of observed X-ray emission. In known clusters, an S-Z decrement of this magnitude would normally be associated with an X-ray luminosity of $\sim 10^{38}$ W. Given the limit in section 4, if this system is similar to those already known to cause S-Z effects, it must lie at $z \gtrsim 1$. Modelling a cluster at $z = 1$, if we assume $\theta_c = 60''$ and an electron temperature of $T_e = 5.8 \times 10^7$ K ($\equiv 5$ keV), we get a good fit to the S-Z data for a central electron density of 3.5×10^3 m^{-3}. Such a cluster has a gas mass inside a 2-Mpc radius of 3.5×10^{14} M$_\odot$. However, the core radius is 500 kpc, very large by the standards of nearby clusters. Assuming a core radius of 300 kpc and the same temperature, we get a best-fit central density of 6.3×10^3 m^{-3}, and a mass within 2 Mpc of 2.0×10^{14} M$_\odot$. In either case, the total mass (gas plus dark matter) of the cluster is $> 10^{15}$M$_\odot$; this derived mass is also insensitive to the assumed redshift of the cluster in the interval $4 \gtrsim z \gtrsim 0.4$. Most "bottom-up" models of structure formation (e.g. cold dark matter, see e.g. Peebles 1993) predict that large clusters should generally be found at low redshifts, so that distant clusters massive enough to cause the CMB imprint we observe should be very rare. It is accordingly now important to search for more clusters via their CMB imprints. This will provide critical information on the space densities of massive systems at redshifts in between the two epochs currently accessible: that at $z \sim 1000$ obtained from primordial CMB anisotropies and that close to the present as seen in galaxy surveys.

Further optical and infrared observations and interpretation are presented in a companion paper (Paper II: Saunders et al. 1996).

6. Conclusions

In Ryle-Telescope observations of the field towards the quasar pair PC1643+4631 A & B we have obtained a firm detection of a CMB decrement of -380 ± 64 μJy in a $110'' \times 175''$ beam. The minimum magnitude of temperature decrement consistent with these observations is 560μK, for a spherical King model with $\theta_c = 60''$. A serendipitous ROSAT observation places a redshift limit of $z \gtrsim 1$ for a cluster with an X-ray luminosity of $\sim 7 \times 10^{37}$ W. For a cluster with a temperature of ~ 5 keV, this implies a total mass of $> 10^{15}$ M$_\odot$, which is only weakly dependant on the assumed temperature and redshift. These results demonstrate that massive systems too faint to be detected easily by their emission can readily be seen by their imprints on the CMB.

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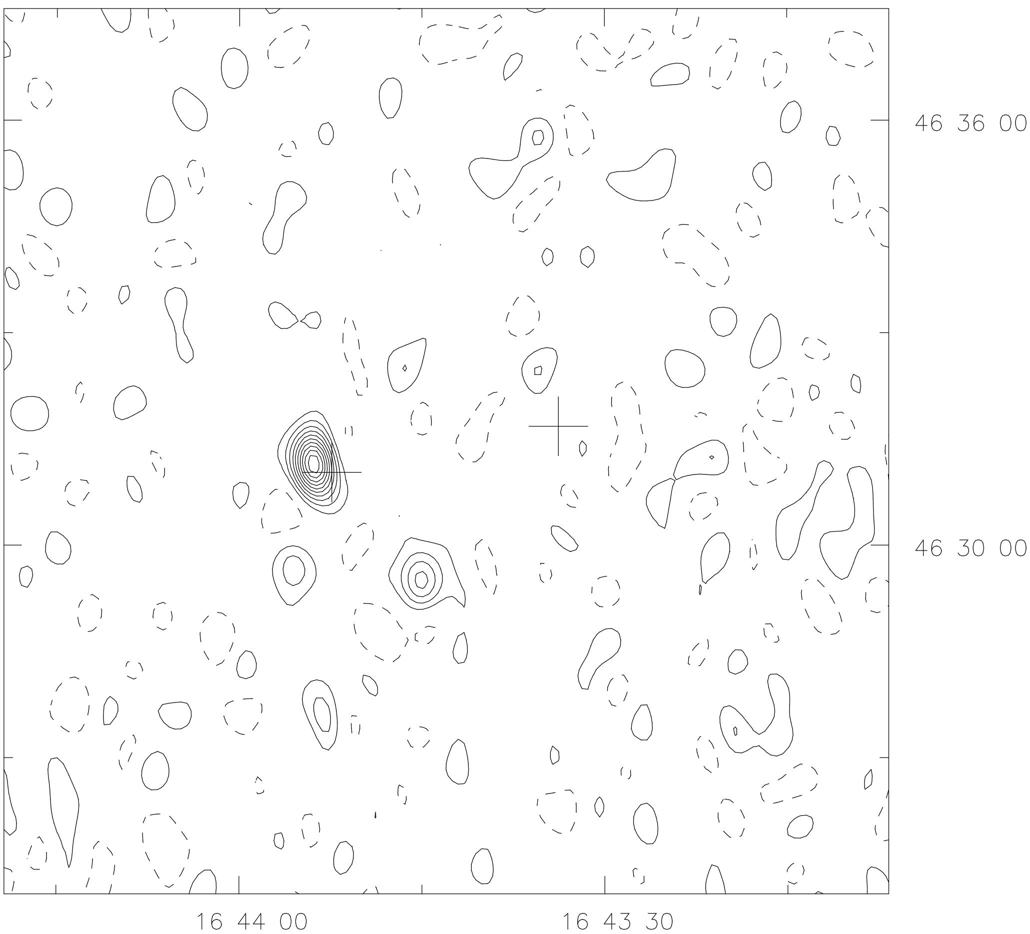

Fig. 1.— PC1643+4631: CLEANed map of the 1.25–5.4 kλ baseline data. The crosses indicate the positions of quasars A (right) and B (left). Contour levels are $-50, 50, 100 \ldots 500\mu$Jy, and the beamsize is $30'' \times 42''$. The bright radiosource is *not* coincident with quasar B given the positional errors. Coordinates are B1950.

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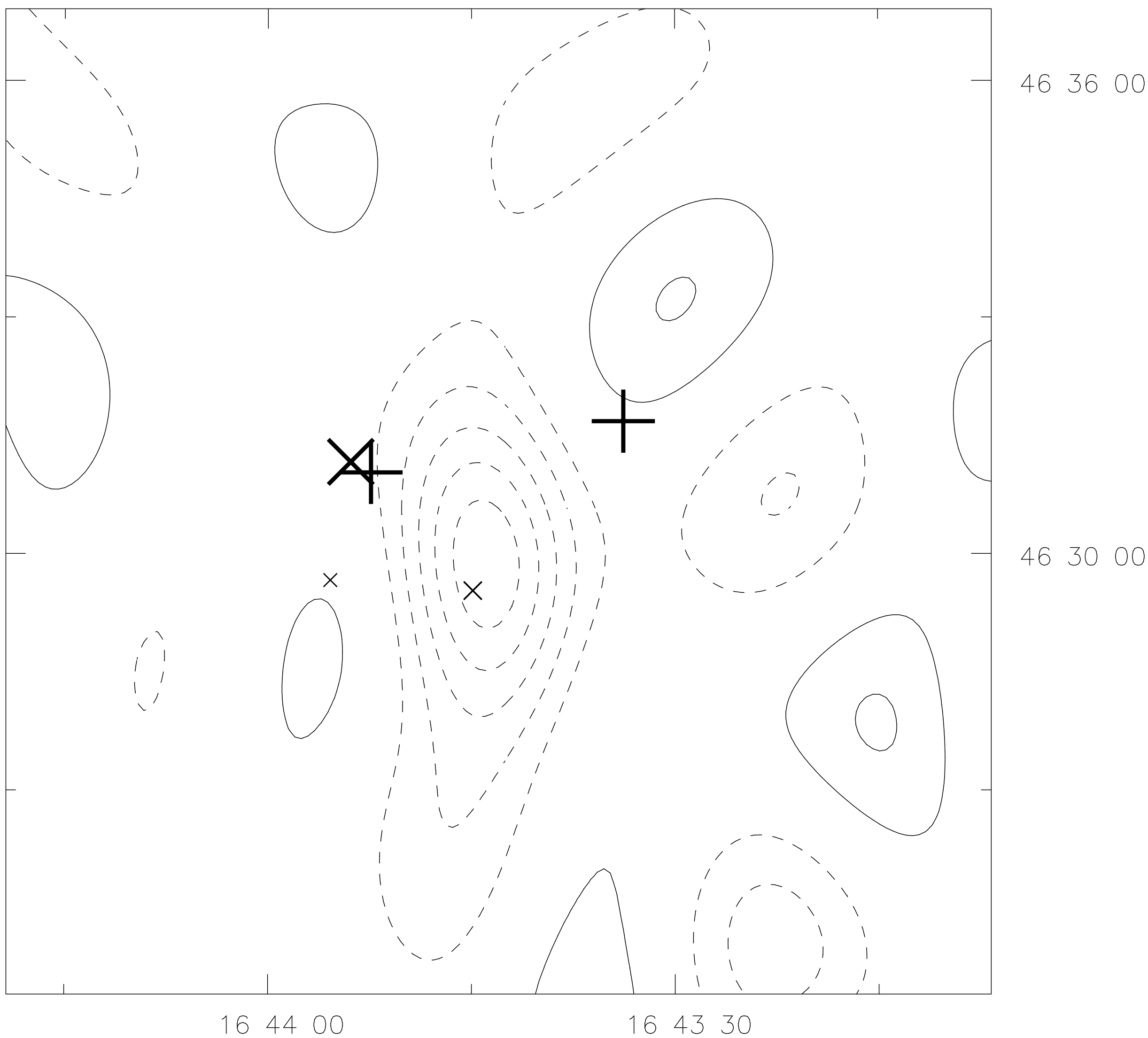

Fig. 2.— PC16433+4631: CLEANed map of the 0.65–1.25 kλ baseline data after source subtraction. The '+' crosses indicate the positions of quasars A (right) and B (left). The '$\times$' crosses show the positions of the sources removed; the size of the symbol is proportional to the removed flux. Contour levels are -325 to $+130\mu$Jy in steps of 65 μJy; dashed contours are negative. Data from the two different pointings have been added together, weighted for the envelope beam attenuation. The final map is not corrected for this attenuation, so the noise level is uniform across the map. Coordinates are B1950.